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Global and Regional Comparative Performance of Linear and Nonlinear Satellite Multichannel Sea Surface Temperature Algorithms

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13. Abstract *(Maximum 200 words)*.

This report summarizes investigations conducted at the Naval Research Laboratory on the accuracy of advanced very high resolution radiometer (AVHRR) satellite sea surface temperature (SST) retrieval techniques. Investigations focused on linear and nonlinear AVHRR atmospheric correction algorithms and their comparative performance relative to global drifting buoy in situ SST observations. Satellite retrievals were matched to drifting buoy SSTs within 2 hours and 10 km from January to December 1990. Emphasis was placed on the bias and root-mean-square difference (rmsd) statistical accuracy of each algorithm for various global regions, atmospheric conditions, and seasonal time periods. Results demonstrate that the nonlinear sea surface temperature (NLSST) algorithm provides consistently better bias and rmsd accuracy statistics relative to the other algorithms tested. Given these results, it is recommended that global satellite SST retrieval processing should utilize the NLSST algorithm for operational retrieval generation. Recommendations are also provided for future algorithm improvement investigations.

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GLOBAL AND REGIONAL COMPARATIVE PERFORMANCE OF LINEAR AND NONLINEAR SATELLITE MULTICHANNEL SEA SURFACE TEMPERATURE ALGORITHMS

1.0 INTRODUCTION

Accurate representation of large-scale and mesoscale sea surface temperature (SST) patterns is valuable for operational Navy activities, weather prediction, and maritime operations. Ocean-feature locations revealed through SST signature are important to naval operations, impacting the performance of military functions such as optimum ship track routing, acoustic surveillance, and search and rescue activities. SST also directly impacts the rate of evaporation and latent heat exchange with the atmosphere, consequently affecting the accuracy of air/sea exchange parameters used by prediction models.

The Navy's large operational domain requires that ample accurate SST information is available throughout the world. From a global perspective, however, in situ SST observations are relatively sparse and regionally located. Ship and buoy measurements can provide between 5,000 and 10,000 global observations each day, but the majority of this data is limited to continental shelf boundaries and major shipping routes. Expendable bathythermograph (XBT) data is even more constrained, providing less than 300 scattered global SST observations daily.

SSTs retrieved from satellite provide between 100,000 and 150,000 daily observations in all global regions limited only by cloud cover conditions. This quantity represents an order of

magnitude increase above all other sources of SST information and provides a valuable input for operational thermal analyses and forecast models. The positive impact that this added information has on thermal analysis results has been demonstrated (Hawkins et al. 1986; May and Hawkins 1988). Satellite SSTs were found to provide improved analysis delineation of ocean mesoscale features, with analysis ocean frontal positions and gradient strengths depicted significantly better when satellite SSTs are used.

In recognition of this added value, the Navy has directed the Naval Oceanographic Office (NAVOCEANO) to operationally generate satellite SST retrievals and make them available for operational Navy utilization. This capability is in place with NAVOCEANO routinely transmitting retrievals over the Shared Processing Network (SPN) communications system on an orbit-by-orbit basis. This effort represents a transition of SST generation capability from the National Oceanic and Atmospheric Administration/National Environmental Satellite Data Information Service (NOAA/NESDIS), which has operationally produced satellite SST retrievals since late 198[illegible], to NAVOCEANO as part of the SPN agreement. [illegible] is a triagency program between the Department of the Navy, the Department of the Air Force, and NOAA in which satellite processing responsibilities, satellite data, and satellite data products are exchanged among agency central processing facilities.

The Naval Research Laboratory (NRL) has been designated as the lead agency for research and development issues affecting satellite SST production. As a result, the Algorithm Research Panel for SST

has been formed to provide scientific guidance and recommendations for SST quality and to examine satellite retrieval algorithms for SST product improvement and possible operational implementation. This panel is chaired by NRL and includes members from NAVOCEANO, the Fleet Numerical Oceanography Center, Air Force Global Weather Central, NOAA/NESDIS, agencies outside SPN operations, and the academic community. Through this panel, the Navy seeks to maintain the most accurate satellite SST product possible and to investigate the potential improvements to SST product quality.

The following study represents an analysis and investigation of the current most widely used satellite SST retrieval techniques. This report seeks to examine the comparative performance of each of these SST algorithms and determine the best candidate for operational use. These algorithms have never previously been compared using a long term validation data set. Therefore a year's worth of carefully screened satellite and drifting buoy SST data is used to derive satellite retrieval algorithms and compare their performance. A short description of each algorithm technique and the comparison method utilized follows. Comparison results and a discussion of the implications are then addressed. Conclusions and recommendations for future investigations are also presented.

2.0 SATELLITE SST RETRIEVAL ALGORITHMS

SST generation from satellite infrared (IR) radiometers has been explored extensively (Anding and Kauth 1970; Maul and Sidran 1972; McMillin 1975; Bernstein 1982; Llewellyn-Jones et al. 1984;

Barton and Cechet 1989). With polar orbiting satellites typically located more than 800 km above the earth's surface, atmospheric effects contaminate the IR signal, partially absorbing and reradiating surface-emitted radiation. Thus, correcting for these atmospheric effects provides the greatest challenge in accurately estimating SST from satellite.

For the satellite sensor spectral bandwidths typically used, these effects are due primarily to atmospheric water vapor, which can vary according to region and air mass type. An atmospheric water vapor correction must then be made to the satellite measured radiances before the absolute SST can be determined. Typically two or more IR measurements at differing wavelengths or viewing angles are employed to determine this atmospheric correction (McMillin and Crosby 1984). The most widely used atmospheric correction technique is the multichannel algorithm used on NOAA Advanced Very High Resolution Radiometer (AVHRR) data. This technique is based upon the differential absorption properties of water vapor in two or three IR channel bandwidths. The AVHRR provides three IR channels centered at 3.7, 11.0 and 12.0 μm, respectively, which can be utilized to automatically correct for atmospheric effects.

Many multichannel algorithms have been derived and used operationally with the NOAA multichannel sea surface temperature (MCSST) algorithm demonstrating a consistent global root mean square difference (rmsd) accuracy less than 0.7°C (Strong and McClain 1984; McClain 1989). Operational retrieval algorithms are empirically derived by regressing satellite channel brightness

temperature retrievals to global drifting buoy SST measurements within specified time and distance constraints. MCSSTs are retrieved globally each day on an orbit-by-orbit basis from Global Area Coverage (GAC) data at a spatial resolution of 8 km (2 x 2 GAC arrays). Details regarding NOAA operational MCSST processing is provided by McClain et al. (1985). The most common technique for obtaining the atmospheric correction utilizes a linear combination of two IR window channels. This approach assumes that the atmospheric absorption due to water vapor is a linear function of the brightness temperature difference of the two window channels. An example of this algorithm is provided by the daytime MCSST algorithm used in this study,

$$MCSST = 1.0364T_4+2.4174(T_4-T_5)+0.6603(T_4-T_5)(\sec(\theta)-1)-283.9486 \quad (1)$$

where T_4 represents the brightness temperature of AVHRR channel 4 centered at 11 µm in Kelvin and T_5 the channel 5 (12 µm) brightness temperature in Kelvin. The MCSST output is in Celcius. The algorithm is referred to as the split window algorithm since channels 4 and 5 "split" the atmospheric absorption window that exists between 10 and 12 µm.

The first term of the equation represents an AVHRR channel (in this case channel 4) brightness temperature estimate of the surface temperature. Theoretically, this value would equal the surface temperature if no intervening atmospheric effects were attenuating the surface emitted radiation. However, this is never the case and

a second term representing the atmospheric correction is needed. Note that the atmospheric correction is provided by the term based on the channel 4 minus 5 difference. McMillin and Crosby (1984) demonstrated that the coefficient of this term, called the gamma parameter, is a function of the channel water vapor absorption coefficients and is found to be constant under certain conditions. These conditions include a wide range of typical atmospheres. Thus, the coefficient for this term is assumed to be static within the MCSST algorithm.

The third term accounts for scan angle corrections with θ representing the satellite zenith angle. This term provides a correction for the increased atmospheric thickness and subsequent atmospheric absorption that occurs between nadir and scan edge. The fourth term is a constant coefficient derived from the linear regression to the buoy data.

The nighttime MCSST algorithm utilizes all three AVHRR IR channels and is referred to as the triple window algorithm. The nighttime algorithm used in this study is as follows:

$$MCSST = 1.0257T_4+1.0055(T_3-T_5)+1.8615(\sec(\theta)-1)-279.729. \qquad (2)$$

Channel 3 (3.7 μm) is available for SST retrievals at night, since solar radiation, which affects the channel signal during the day, is not present in the channel signal at night. This channel provides the added benefit of greater atmospheric transmissivity

than either channel 4 or 5 (May et al. 1993). Thus, the difference between channels 3 and 5 is used for the atmospheric correction term and provides a greater sensitivity to atmospheric effects and a theoretically more accurate retrieval than the split window technique.

Recent research has demonstrated that the gamma parameter, or coefficient for the second term of the MCSST equation, is not a constant but actually a function of both scene temperature and water vapor amount (Walton 1988). The constant gamma assumption is particularly suspect for very moist and very dry atmospheric conditions. These findings have led to nonlinear correction approaches. One such algorithm, the cross product sea surface temperature (CPSST) utilizes cross-product terms of the multiple channel data to provide an equation correction term coefficient that varies in value based on channel brightness temperature magnitude and interchannel temperature difference. The result is an equation that no longer assumes a constant linear correction for all atmospheres, but rather one that varies the correction according to atmospheric conditions in the form of channel brightness temperature changes.

Equation 3 represents the daytime split window CPSST equation used in this study:

$$CPSST = 0.9621T_5+\left(\frac{0.1967T_5-52.1811}{0.2045T_5-0.1694T_4-8.137}\right)(T_4-T_5+0.295) \\ +0.7538(T_4-T_5)(\sec(\theta)-1)-262.275. \tag{3}$$

Note that the coefficient pertaining to the channel 4 minus 5 difference term is no longer constant but rather a function of the channel 4 and 5 magnitude, as well as channel temperature difference.

The nighttime triple window CPSST algorithm derived for this study is as follows:

$$CPSST = 0.9624T_4+\left(\frac{0.1906T_4-51.6178}{0.1936T_5-0.0865T_3-25.889}\right)(T_3-T_5+1.974)$$
$$+1.9806(\sec(\theta)-1)-262.438. \quad (4)$$

A consequence of the CPSST equation is that more terms are added into the SST calculation and the algorithm becomes more sensitive to factors that can generate variability in channel brightness temperatures such as sensor noise, cloud contamination, and diurnal heating of the surface. Thus, anticipated improvements relative to the MCSST retrievals have been difficult to realize operationally.

A more simplified nonlinear retrieval technique has been introduced called the nonlinear sea surface temperature (NLSST) (Walton et al. 1990). Similar to the CPSST theory, the NLSST assumes that the gamma parameter should vary with atmospheric conditions. Rather than utilizing sensor channel brightness temperatures to do this, however, the NLSST forces the gamma parameter to be a function of a field analysis or surface

temperature valid at each specified retrieval earth location. Equation 5 demonstrates the daytime split window NLSST form.

$$NLSST = 0.9607T_4 + 0.0829T_f(T_4 - T_5) + 0.7296(T_4 - T_5)(\sec(\theta) - 1) - 261.201. \tag{5}$$

T_f represents the surface temperature estimate, which can be obtained from a field analysis temperature or even an MCSST retrieval. The algorithm sensitivity to sensor noise, cloud contamination, and daytime solar heating is lessened due to the decreased dependence of the gamma parameter to sensor channel brightness temperatures. The algorithm is more sensitive to the field analysis accuracy; however, this sensitivity is relatively small due to the magnitude of the correction term coefficient.

Whereas the CPSST utilizes channel brightness temperatures to define the gamma parameter dependence on scene temperature and water vapor, the NLSST defines the dependence as a function of scene temperature only. In a simple and indirect way, the water vapor dependence is also accounted for since atmospheric water vapor concentration is typically highest in the tropics where SST is warm and lowest at high latitudes where SST is also low. The nighttime triple window NLSST algorithm derived for this study is as follows:

$$NLSST = 1.02T_4 + 0.78(T_3 - T_5) + 0.0075T_f(T_3 - T_5) + 1.8625(\sec(\theta) - 1) - 277.98. \tag{6}$$

3.0 ALGORITHM COMPARISON METHOD

Satellite SST retrieval matchups to drifting buoy observations were obtained for the entire year of 1990. Matchups from the NOAA/NESDIS monthly matchup database were combined to compare the accuracy of three different algorithm techniques, the MCSST, CPSST, and NLSST equations. The data from 1990 was used because this year had no significant volcanic aerosol contamination in the atmosphere; the NOAA-11 thermal calibration problem in 1989 data had been resolved, and the NOAA-11 AVHRR channel 3 produced some of the most noise-free data from that bandwidth than any previous NOAA satellite.

The satellite-buoy matchups were restricted to matches within 2-hour and 10-km time and distance differences. This constraint was utilized to eliminate rmsd errors associated with spatial separations and time intervals (Minnett 1991). Satellite retrievals matched to more than one buoy observation were filtered to retain only the buoy matchup closest in time and distance. The resulting data set consists of 1370 daytime and 1184 nighttime global matchups.

In order to compare the accuracy of the three algorithm techniques, the daytime and nighttime matchup data sets were each split in half to produce dependent data sets from which algorithms were derived and independent data sets to compare the derived algorithm results against. The dependent and independent data sets were created by sorting the matchups by time of the year and then

placing every other matchup into the dependent and then the independent data set. MCSST, CPSST, and NLSST algorithms were derived from the dependent data set by regressing the proper satellite parameters to the buoy in situ observations. Equations 1 through 6 represent the derived algorithms. Two NLSST algorithms were studied. One utilized the corresponding MCSST result for T_f. The other NLSST utilized the NOAA/NESDIS supplied field analysis temperature as the T_f term. These will be referred to as NLSST(M) and NLSST(F), respectively.

The derived algorithms were applied to the independent data set for comparative global performance. This data set was further stratified by region and atmospheric moisture classification as demonstrated by the difference between channels 4 and 5 of the AVHRR. This provided a regional and air mass performance comparison for each of the globally derived algorithms. The data was also divided by SST magnitude to investigate accuracies at both cold and warm SSTs. Lastly, the data was split into monthly data sets to provide a seasonal performance analysis.

4.0 RESULTS

Table 1 lists the bias (in parentheses) and rmsd accuracy statistics of the daytime algorithms. The results have been stratified by region, air mass type, and SST magnitude. Each algorithm demonstrates global bias accuracy within 0.1°C and rmsd accuracy of 0.7°C. Such global accuracies have been demonstrated in

Table 1 - Daytime Regional Statistics

Region	# of Matches	MCSST	CPSST	NLSST(M)	NLSST(F)
Global	685	(0.01) 0.66	(0.0) 0.64	(0.02) 0.65	(0.0) 0.58
25°N-70°N	292	(0.13) 0.62	(0.08) 0.57	(0.06) 0.57	(0.04) 0.53
25°N-25°S	302	(-0.11) 0.68	(-0.07) 0.70	(0.0) 0.72	(-0.03) 0.64
25°S-70°S	91	(0.0) 0.71	(-0.03) 0.63	(-0.02) 0.61	(-0.02) 0.58
N. Pac.	39	(0.08) 0.54	(0.06) 0.48	(0.08) 0.45	(0.06) 0.44
N. Atl.	213	(0.16) 0.65	(0.09) 0.61	(0.07) 0.60	(0.06) 0.57
Indian	76	(0.03) 0.64	(0.02) 0.60	(0.04) 0.58	(0.03) 0.54
Trop. Pac.	246	(-0.10) 0.68	(-0.05) 0.70	(0.04) 0.73	(0.01) 0.63
East Pac.	230	(-0.09) 0.66	(-0.07) 0.65	(0.01) 0.68	(-0.01) 0.59
West Pac.	47	(-0.12) 0.62	(0.04) 0.76	(0.13) 0.77	(0.09) 0.66
$0<T_4-T_5<1$	133	(-0.25) 0.60	(-0.11) 0.55	(-0.10) 0.53	(-0.09) 0.52
$1<T_4-T_5<2$	387	(0.12) 0.62	(0.01) 0.59	(0.01) 0.58	(-0.01) 0.55
$2<T_4-T_5<3$	141	(-0.02) 0.73	(0.03) 0.72	(0.13) 0.76	(0.09) 0.64
0<SST<25	394	(0.09) 0.64	(0.05) 0.59	(0.02) 0.58	(0.01) 0.55
SST>25	291	(-0.12) 0.67	(-0.07) 0.70	(0.02) 0.72	(-0.01) 0.62

the past as typical values using AVHRR algorithms (McClain 1989). The daytime CPSST algorithm improves upon MCSST global results, providing a slightly more accurate global rmsd and bias. The NLSST(M) global statistics do not improve on the CPSST results. However, MCSST, CPSST, and NLSST(M) bias and rmsd statistics are all within 0.02°C, demonstrating comparable global results regardless of which algorithm is used. Use of the field temperature for the surface temperature estimate NLSST(F) significantly improves the global retrieval accuracy relative to the other three algorithms. Retrieval rmsd statistics improve from 0.66°C to 0.58°C using NLSST(F). This accuracy improvement is evident not only globally but also for all but one of the regional comparisons as well. Figure 1 depicts the rmsd of the algorithms for each global region. Use of a nonlinear algorithm that utilizes a surface temperature estimate that is obtained independent of the AVHRR sensor channel data significantly improves the retrieval accuracy.

Analysis of regional daytime statistics demonstrates that the algorithms tend to exhibit a warm bias in the northern latitudes and a negative bias in the tropics. The MCSST algorithm demonstrates the largest bias variation between regions (0.24°C) with the NLSST algorithms showing the smallest bias variation (0.06°C).

A likely reason for the regional bias fluctuations could possibly be attributed to changes in predominant atmospheric characteristics between regions. The atmospheric moisture

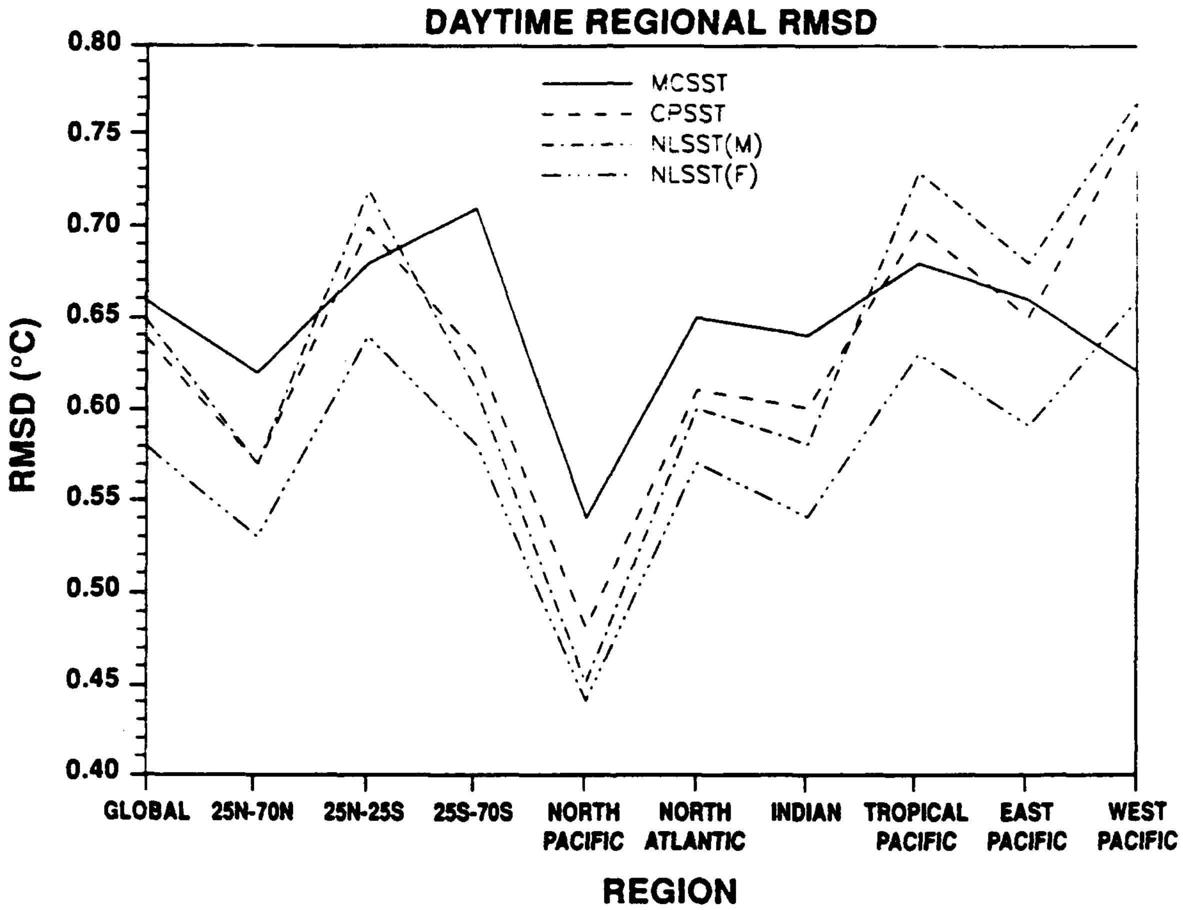

Fig. 1 - Root mean square difference error for MCSST, CPSST, NLSST(M), and NLSST(F) daytime algorithms for various global regions

stratification rows, depicted by the channel 4 minus 5 difference, demonstrate that the SST algorithms tend to underestimate SST for dry atmospheres and overestimate SST for moist atmospheres. Since tropical atmospheres are typically more moist than those at high latitudes, we should expect the retrieval algorithms to exhibit a positive bias in the tropics and a negative bias in the higher latitudes. The regional bias results obtained, however, are opposite of what is expected due to atmospheric moisture.

Table 1 also includes a stratification according to SST magnitude. This stratification was selected based on the fact that SSTs less than 25°C are typical of northern latitude data, and SSTs greater than 25°C are representative of tropical retrievals. Analysis of these statistics demonstrates that the retrieval algorithms tend to overestimate SST when it is less than 25°C and underestimate SST when it is warmer than 25°C. This fact is most evident for the MCSST and CPSST algorithms. The NLSST algorithms significantly improve upon this temperature dependency.

The conclusion is that the regional bias fluctuation observed between the tropics and northern latitudes is not related strictly to atmospheric moisture content but rather is more dependent upon the scene temperature. Since the NLSST gamma parameter is a function of the scene temperature, this daytime algorithm provides the least variation of bias between regions.

Table 2 lists the bias and rmsd accuracy statistics for the nighttime algorithms. Interestingly, no significant difference in global statistics is readily obvious between the various algorithm

Table 2 - Nighttime Regional Statistics

Region	# of Matches	MCSST	CPSST	NLSST(M)	NLSST(F)
Global	592	(0.01) 0.38	(0.02) 0.39	(0.02) 0.38	(-0.01) 0.38
25°N-70°N	165	(0.22) 0.47	(0.10) 0.48	(0.12) 0.48	(0.09) 0.46
25°N-25°S	363	(-0.03) 0.33	(-0.01) 0.34	(-0.02) 0.32	(-0.04) 0.32
25°S-70°S	64	(-0.04) 0.43	(-0.02) 0.45	(-0.03) 0.43	(-0.06) 0.43
N. Pac.	44	(0.11) 0.28	(0.11) 0.30	(0.12) 0.28	(0.09) 0.26
N. Atl.	118	(0.12) 0.53	(0.11) 0.54	(0.13) 0.54	(0.10) 0.52
Indian	35	(0.01) 0.46	(0.04) 0.47	(0.02) 0.46	(0.0) 0.46
Trop. Pac.	304	(-0.02) 0.30	(0.01) 0.31	(0.0) 0.30	(-0.02) 0.30
East Pac.	234	(-0.03) 0.30	(-0.02) 0.31	(-0.01) 0.30	(-0.04) 0.30
West Pac.	90	(0.0) 0.29	(0.06) 0.32	(0.02) 0.29	(0.0) 0.30
$0<T_4-T_5<1$	28	(-0.20) 0.50	(-0.06) 0.47	(-0.18) 0.50	(-0.17) 0.50
$1<T_4-T_5<2$	360	(-0.02) 0.39	(-0.01) 0.41	(0.0) 0.39	(-0.03) 0.39
$2<T_4-T_5<3$	185	(0.07) 0.36	(0.07) 0.36	(0.09) 0.36	(0.05) 0.35
0<SST<25	226	(0.07) 0.47	(0.08) 0.47	(0.08) 0.47	(0.05) 0.46
SST>25	366	(-0.03) 0.32	(-0.01) 0.32	(-0.02) 0.32	(-0.04) 0.32

types. Figure 2 reveals the similarity of the algorithm rmsd accuracies by region. It is apparent that the use of channel 3 at nighttime significantly improves MCSST retrieval accuracy relative to the daytime split window approach. Nighttime algorithm global accuracies were found to be 0.38°C. Most likely this improved accuracy is a result of the greater atmospheric transmissivity of channel 3 and the fact that the NOAA-11 channel 3 was remarkably noise-free in 1990. The nonlinear and linear algorithms demonstrate comparable results, suggesting that channel 3 helps to also eliminate nonlinear atmospheric effects that are present when using channels 4 and 5 only. Thus, nonlinear techniques provide minimal improvement relative to the MCSST results obtained.

Analysis of the nighttime regional statistics shows that a warm bias exists in the northern latitudes as was similarly observed in the daytime matches. A significant negative bias in the tropics is not evident, however, in the nighttime data. A large majority of the nighttime matches were obtained from the tropics, though, leading to possible algorithm derivations more accurate for tropical atmospheres. A consequence of this is that biases can exist in other regions such as the northern latitudes.

The nonlinear techniques demonstrate less regional bias fluctuation than the MCSST algorithm results although this improvement is not as great as the results obtained from the daytime algorithms. The scene temperature dependence observed in the daytime results is also evident in the nighttime data. It is interesting, though, that the NLSST does not significantly improve

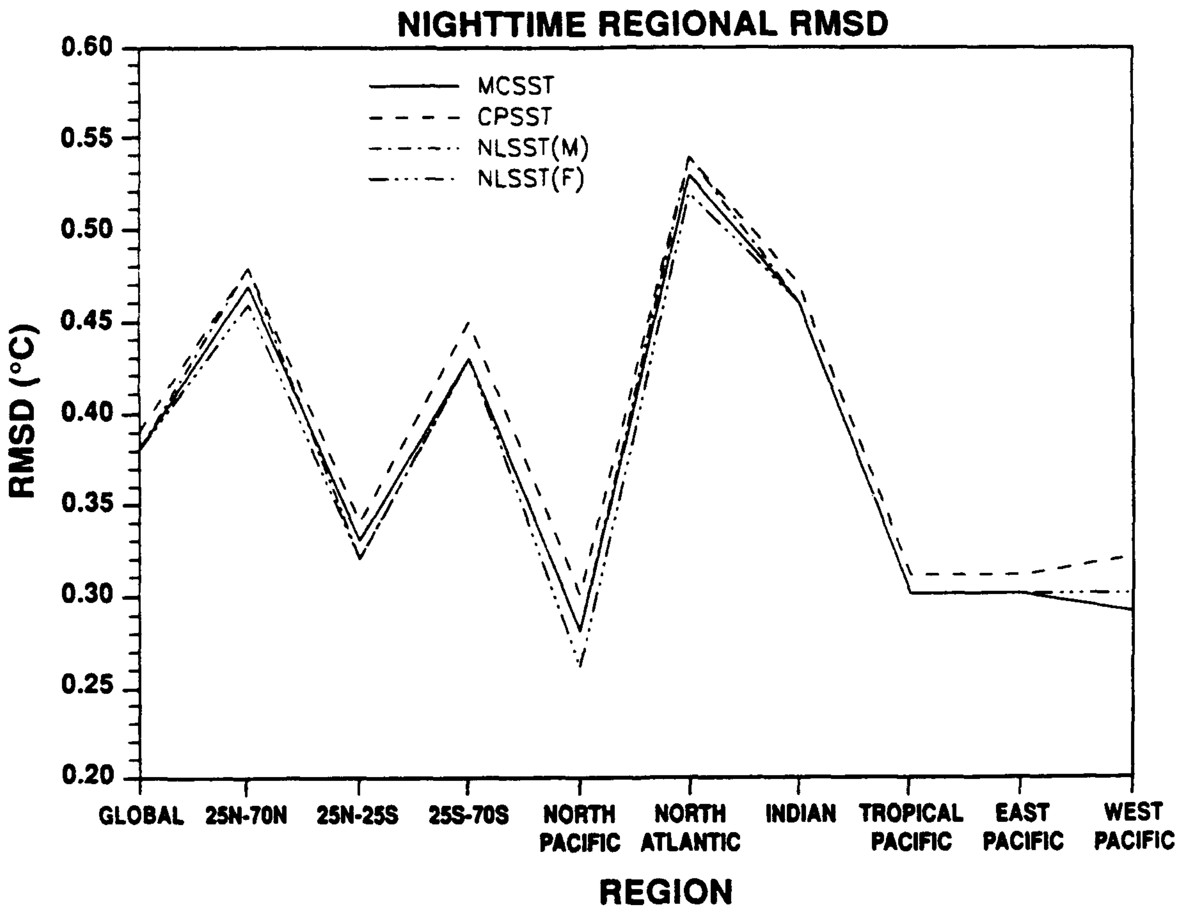

Fig. 2 - Root mean square difference error for MCSST, CPSST, NLSST(M), and NLSST(F) nighttime algorithms for various global regions

on the MCSST scene temperature dependence even though the NLSST algorithm gamma parameter is a function of scene temperature.

Tables 3 and 4 list the algorithm accuracy statistics according to month. Daytime and nighttime algorithm rmsd accuracies demonstrate no definite seasonal pattern - fluctuating month to month. Monthly bias statistics do indicate a slight tendency for negative bias in the late spring and summer months with a positive bias in the fall and winter months. This result may be a function of the prevailing atmospheric conditions associated with buoy matchup locations each month. Since the majority of buoy matchup data is obtained from tropical and northern latitudes, seasonal atmospheric changes in these regions could affect the predominant global matchup atmospheric conditions each month. Overall, NLSST(F) provides the best monthly rmsd accuracy results. Performance of the monthly NLSST(F) bias accuracy, however, is not significantly better relative to the other algorithms tested. This result is surprising given the regional bias results obtained in Tables 1 and 2.

5.0 DISCUSSION

It is evident that the MCSST use of a constant gamma parameter is not always adequate for retrieving accurate SSTs under all atmospheric conditions. This fact is especially pronounced in the daytime data, which demonstrate large bias and rmsd fluctuations between global regions. The daytime MCSST algorithm bias

Table 3 - Daytime Monthly Statistics

ıth	# of Matches	MCSST	CPSST	NLSST(M)	NLSST(F)
January	77	(-0.07) 0.73	(-0.12) 0.73	(-0.11) 0.76	(-0.12) 0.68
February	36	(0.07) 0.67	(0.08) 0.67	(0.14) 0.71	(0.07) 0.64
March	65	(0.01) 0.64	(0.02) 0.60	(0.04) 0.61	(0.02) 0.58
April	56	(0.07) 0.72	(0.02) 0.65	(0.05) 0.63	(0.03) 0.56
May	52	(-0.09) 0.67	(-0.07) 0.69	(-0.05) 0.68	(-0.06) 0.57
June	50	(-0.21) 0.60	(-0.24) 0.57	(-0.21) 0.55	(-0.22) 0.51
July	66	(0.03) 0.72	(0.0) 0.74	(0.02) 0.74	(0.0) 0.66
August	71	(0.0) 0.77	(-0.06) 0.74	(-0.01) 0.74	(-0.02) 0.66
September	48	(0.01) 0.64	(0.03) 0.58	(0.08) 0.56	(0.07) 0.52
October	57	(0.01) 0.51	(0.04) 0.45	(0.06) 0.45	(0.04) 0.44
November	40	(0.07) 0.59	(0.09) 0.64	(0.08) 0.61	(0.07) 0.59
December	67	(0.18) 0.57	(0.21) 0.57	(0.23) 0.61	(0.19) 0.56

Table 4 - Nighttime Monthly Statistics

Month	# of Matches	MCSST	CPSST	NLSST(M)	NLSST(F)
January	44	(0.05) 0.45	(0.07) 0.45	(0.07) 0.45	(0.03) 0.44
February	39	(0.03) 0.33	(0.04) 0.33	(0.04) 0.33	(0.02) 0.32
March	42	(−0.03) 0.32	(−0.02) 0.38	(−0.02) 0.38	(−0.04) 0.33
April	48	(−0.06) 0.30	(−0.02) 0.31	(−0.05) 0.31	(−0.06) 0.30
May	49	(−0.11) 0.36	(−0.07) 0.35	(−0.09) 0.35	(−0.11) 0.36
June	42	(−0.04) 0.45	(−0.03) 0.44	(−0.03) 0.44	(−0.05) 0.44
July	54	(0.07) 0.50	(0.06) 0.50	(0.08) 0.50	(0.04) 0.49
August	64	(−0.09) 0.40	(−0.08) 0.41	(−0.07) 0.41	(−0.10) 0.40
September	57	(0.05) 0.43	(0.07) 0.45	(0.06) 0.45	(0.04) 0.43
October	59	(0.08) 0.36	(0.10) 0.35	(0.09) 0.35	(0.07) 0.35
November	39	(0.03) 0.27	(0.03) 0.29	(0.05) 0.29	(0.02) 0.28
December	56	(0.08) 0.36	(0.08) 0.40	(0.10) 0.40	(0.07) 0.36

difference between tropical and northern high latitude atmospheres is approximately 0.24°C. The MCSST algorithm underestimates SST at the tropics and overestimates SST at northern high latitudes. By deriving a global MCSST algorithm to cover all regions of the world, the resulting algorithm overestimates in some regions on average and underestimates in others.

The CPSST and NLSST algorithms vary the correction term coefficient nonlinearly, which helps to limit the bias fluctuation between world regions. Although the nonlinear technique employed by the daytime CPSST algorithm decreases the bias variation somewhat between regions, the bias still varies 0.15°C between the tropics and the northern latitudes. Also, regional CPSST rmsd accuracies are slightly improved. The daytime NLSST(M) and NLSST(F) algorithms further reduce the bias fluctuation with differences between tropics and high latitudes reduced to 0.07°C using these algorithms. NLSST(F) improves overall daytime rmsd accuracy roughly 0.08°C relative to the MCSST algorithm. These results demonstrate that a nonlinear correction significantly improves both the bias and rmsd accuracy of daytime satellite retrievals.

Nighttime algorithm comparisons demonstrate minimal difference between the algorithm types tested. Global accuracy statistics of the MCSST algorithm are a remarkable 0.38°C rmsd. Algorithm error due to sensor channel noise alone is calculated to be 0.16°C (Table 5). Deschamps and Phulpin (1980) estimate another 0.1°C error due to global atmospheric variation just for the triple window

Table 5 - Algorithm Sensor Noise

Algorithm	Daytime	Nighttime
MCSST	0.21	0.16
CPSST	0.33	0.17
NLSST(M)	0.23	0.16
NLSST(F)	0.20	0.16

algorithm without considering sensor noise. Thus, the nighttime MCSST results are quite impressive given that the theoretically attainable accuracy is 0.26°C.

Neither the CPSST or NLSST demonstrate any improvement over the linear MCSST rmsd results globally. Some reduction in regional bias variation is apparent when using the nonlinear algorithms. The MCSST bias fluctuates 0.25°C between the tropics and high northern latitudes. Both the CPSST and NLSST algorithms reduce the bias variation to less than 0.14°C. This demonstrates that the nonlinear algorithm bias is less sensitive to changing atmospheric conditions than linear algorithms are.

The general reason why the nighttime MCSST algorithm produces good results is due to the input from channel 3. This channel is less affected by atmospheric effects than channels 4 and 5, allowing for increased atmospheric correction capability. Atmospheric water vapor variations that occur globally will affect channel 3 the least. Add to this the fact that NOAA-11 has demonstrated a very noise-free channel 3, and this data set provides remarkably accurate satellite SST retrieval results. It is also apparent that the channel 3 minus channel 5 difference provides a much better linear correction for atmospheric effects than the split window technique that uses channels 4 and 5. Global average nighttime rmsd accuracy statistics are 0.2°C better than daytime rmsd accuracies.

Daytime split window sensor noise error varies considerably between the various algorithm types. This fact is displayed in

Table 5. The daytime MCSST algorithm exhibits sensor noise error of 0.21°C due solely to channels 4 and 5. This error increases to 0.33°C for the CPSST, which possibly explains why the daytime CPSST does not produce any better rmsd accuracy results than it does. The main reason for the increased CPSST algorithm noise is due to the addition of several more equation terms, which will each be affected by sensor channel noise. The NLSST algorithm noise error is decreased significantly relative to the CPSST algorithm, with the NLSST(F) calculated assuming that the surface temperature estimate has no error. Using MCSST as the surface temperature estimate, however, does not significantly increase the noise for NLSST(M).

Deschamps and Phulpin (1980) estimate daytime split window algorithm errors of 0.51°C due to atmospheric variations about the globe. Thus, the total MCSST split window error expected is 0.72°C. The MCSST result obtained by this study is better than expected at 0.66°C. CPSST and more so NLSST(F), clearly demonstrate that daytime rmsd accuracy improvements can be attained using a nonlinear approach. Even though the CPSST daytime algorithm possesses greater sensor noise sensitivity, it still outperforms the MCSST algorithm. By decreasing the nonlinear algorithm sensor noise sensitivity, as is done with the NLSST(F) equation, the benefits of a nonlinear approach are realized.

It is apparent that the use of a nonlinear algorithm provides significantly better SST bias and rmsd accuracy results. This fact is particularly evident in the daytime algorithms. Use of a

constant atmospheric correction term coefficient as utilized by the MCSST algorithm, does not work well for all atmospheric air mass type corrections. Both the CPSST and NLSST nonlinear algorithms provide improved daytime algorithm accuracy results by varying the atmospheric correction term coefficient. The use of nonlinear algorithms also decreases the fluctuation of bias errors that exist between different regions of the globe. The nonlinear NLSST(F) reduces these bias variations the most; however, it is apparent that more improvement in accuracy can be made.

The NLSST algorithm provides better results than the CPSST due to its reduced sensitivity to variability in channel brightness temperatures. Since the gamma parameter is truly a function of the channel water vapor absorption coefficients, it is sensitive to changes in water vapor content and water vapor temperature. NLSST attempts to account for this sensitivity by a simple but indirect method, namely, as a function of the underlying surface temperature. This technique appears to generate decent results on an overall global basis because both water vapor amount and temperature tend to increase as the surface temperature increases. It is obvious however that such a technique will not work well for all atmospheric situations. Thus, what is really needed to improve retrieval accuracy is more precise information on the atmospheric water vapor content and water vapor temperature.

Harris and Mason (1992) have demonstrated that theoretical improvement is possible if the correction term coefficient is allowed to vary as a function of the multiple channel atmospheric

transmittance ratio change. Since the transmissivity changes in channels 4 and 5 are mainly caused by water vapor, it may be possible to utilize accurately obtained satellite water vapor retrievals to improve the atmospheric correction. It is demonstrated that the atmospheric transmissivity of channels 4 and 5 change differently with changing air mass types. Thus, the use of a constant coefficient produces errors. Although the CPSST and NLSST attempt to account for this nonlinear relationship, each is limited in how it corrects for the overall effect.

The difference between channels 4 and 5 has been utilized in the past for estimating total atmospheric water vapor content (Dalu 1986). However, the accuracy of this estimate is approximately 0.5 g/cm^2. Considering that global atmospheric water vapor ranges from roughly 0.5 to 6.0 g/cm^2, this error may be the limiting factor as to why the split window atmospheric correction term performs no better than it does. Using the channel 4 minus 5 difference to correct for atmospheric effects, which are mainly due to water vapor, will demonstrate the error inherit to the water vapor retrieval accuracy of the sensor.

Use of a passive microwave satellite sensor such as the Special Sensor Microwave/Imager (SSM/I) aboard the Defense Meteorological Program satellites could significantly increase the accuracy of atmospheric water vapor estimates. Hollinger (1989) has demonstrated water vapor retrieval accuracies of 0.24 g/cm^2 using the 19, 22, and 37 GHz channels. This accuracy provides a 50% improvement over the results available using the split window AVHRR

channels. It is theoretically possible that if the atmospheric correction coefficient or gamma parameter is allowed to vary as a function of an accurate atmospheric water vapor retrieval, that some improvement to the SST accuracy results could be obtained. Both the CPSST and NLSST algorithms are currently limited to information on split window channel differences and estimates of the surface temperature magnitude.

Schluessel et al. (1987) have demonstrated that improved accuracy is possible if the regression equation is expanded to include terms containing atmospheric temperature information from the high resolution infrared radiation sounder (HIRS) sensor. Terms that utilize the water vapor channel and three CO_2 channels provide information on the atmospheric water vapor content and air temperature in the lower troposphere. The result is an improved correction since both the water vapor and air temperature dependence of the atmospheric correction is better described. The referenced study utilized HIRS data as a separate equation term rather than incorporating it into the gamma parameter. Since HIRS data is available coincident with AVHRR data, investigation into the gamma parameter as a function of HIRS channel sensor data should be pursued.

Beginning with the launch of NOAA-K, each NOAA polar orbiter will carry Advanced Microwave Sounding Unit-A (AMSU-A) and AMSU-B sensors. Data obtained by these two sensors will provide air temperature and humidity profiles from the surface to the stratosphere coincident with AVHRR data. Incorporation of this

information into SST retrieval algorithms should be examined since it offers possible retrieval accuracy improvement.

6.0 SUMMARY

The comparative performance of the linear MCSST, and nonlinear CPSST, and NLSST algorithms has been examined. Algorithms were derived from and compared to carefully screened satellite-buoy SST matchups obtained between January and December 1990. Globally and seasonally diverse matchups were restricted to 2-hour and 10-km difference constraints to eliminate rmsd errors associated with matchup time and spatial differences. Daytime and nighttime algorithms were derived from one-half of the data matchups and compared to the remaining data. Care was taken to provide comparable seasonal and global matchup distributions within these two data sets.

Results show that the nonlinear algorithms provide significantly better SST bias and rmsd accuracy results on a consistent basis. This is true for both global and regional stratifications. Best accuracy results are obtained with the NLSST algorithm that uses an atmospheric correction term coefficient that is a function of an SST field analysis temperature. These results are particularly pronounced in the daytime algorithms and less so for nighttime algorithms. Daytime MCSST global rmsd accuracies of 0.66°C are improved to 0.58°C using NLSST. Although the nonlinear CPSST algorithm should theoretically provide similar improvements,

it suffers from greater sensitivity to sensor channel noise due to its numerous coefficients and equation terms.

Use of channel 3 at night provides a remarkably accurate linear MCSST algorithm which is difficult to improve upon using nonlinear techniques. The greater transmissivity of channel 3 provides nighttime retrieval estimates that are accurate to 0.38°C globally. Both CPSST and NLSST demonstrate similar accuracies globally. This accuracy is 0.2°C better than that presently obtainable using only channels 4 and 5 and demonstrates the importance of channel 3 to SST retrieval accuracy.

NLSST also exhibits the best rmsd accuracy results on a monthly basis. No seasonal trend in daytime or nighttime rmsd values was observed for any of the algorithms. Each algorithm demonstrated a slight tendency for negative bias in the late spring and summer months and a positive bias during the fall and winter months.

The use of nonlinear algorithms decreases the variation of bias errors that occur between different regions of the world. This fluctuation is most pronounced between the tropics and high latitudes where daytime MCSST bias changes 0.24°C. Negative bias values occur in the tropics and positive values at the high latitudes. These fluctuations appear to be due to an observed scene temperature dependence of the algorithm. The NLSST(F) algorithm reduces the daytime bias variations the most since it varies the gamma parameter coefficient as a function of scene temperature. Similar reduction in nighttime bias fluctuations are also obtained

using the NLSST(F) algorithm. Given these results it is recommended that global satellite SST retrieval processing should utilize the NLSST(F) algorithm for both daytime and nighttime retrieval generation.

Although the NLSST(F) provides the best overall accuracy results, considerable improvement is still necessary if satellite SSTs are ever to attain the 0.3°C rmsd accuracy desired by the climate global change research community. Limitations to the current algorithms could be improved upon to increase accuracy results. Investigations into the possible incorporation of remotely sensed water vapor and air temperature data into the AVHRR atmospheric correction should be pursued. Such data would provide more accurate information on atmospheric water vapor content and water vapor temperature, the two primary variables affecting atmospheric attenuation of the surface emitted radiance. Most likely, the greatest improvements will be realized in the daytime algorithms.

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